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EXPERIMENTAL STUDY AND MODELLING TO DEVELOP STANDARDIZED-MODULARIZED RESTRICTED DEPTH HIGHWAY GIRDERS

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ABSTRACT: The development in transportation requires the faster accomplishment of various tasks, including the bridge superstructure construction. In the present study, the authors developed the twin-T shape as a standardized and modularized cross-section for prestressed post-tensioned girders of the highway bridge deck, especially across railways, based on established R & D results. This paper also focused on the solution to the longitudinal crack in the multi-girder bridge deck. The enhanced features adopted in study, like the evolved girder shape, integrating top slab and shear key and usage of high-performance concrete, reduce the depth and increase cost-effectiveness, durability and safety. High strength high-performance concrete (HS-HPC) of M75 grade is necessary for casting the girder of cross-section to satisfy the design requirements. The cross-section developed is suitable to make bridges spanning from 15m to 45m. The authors conducted an experimental study on two girder specimens of similar features of prototype girders, using the M55 mix. The modelling, simulating the experimental studies, was developed through the ABAQUS software, and the same was calibrated and validated with the experimental results.

KEYWORDS: Accelerated bridge construction; Standardization and Modularization; Post-tensioned-HS-HPC; ABAQUS; ROB.

1 INTRODUCTION

Fast completion of any Highway network is possible only by the speedy completion of bridges. That is possible by adopting standardized, modular, and precast constructions. The authors developed a twin-T cross-section of the post-tensioned pre-stressed concrete superstructure of highway bridges suitable for standardization and conducted an experimental study on girder specimens of this cross-section to observe the structural performances narrated in the upcoming sections. The same has been modelled in FEM through the ABAQUS software to see the adaptability of the same type cross-section of bridges for medium spans ranging from 15m to 45m. A highway bridge crossing over a busy railway track was the critical design situation selected in this study. The achievement of the Standardized and modularized bridge superstructure will lead to Accelerated Bridge Construction (ABC).

2 NEED AND BACKGROUND OF THE STUDY

The depth of construction of the bridge superstructure will become the prime factor for deciding the length of Road Over Bridge (ROB) across railway, while maintaining the permitted gradient on both approaches of the bridges. The various concepts behind the planning of such bridges are mainly; keeping minimum specified vertical clearance, restricted depth of bridge, minimum land acquisition, effective launching and standardized modular shutter with minimum modification for each bridge span. [1].

Accordingly, the design situations satisfied will be; minimum disturbance to train traffic, fast completion, not affecting the required vertical clearance without changing the existing junction or bridge structure if any in the merging end of the approach, safe and speedy launching, speedy formal sanctions, managing of minor skew angles, demolition and reusing of bridge units and using green and aesthetic structure. Additionally, the superstructure should be safe, serviceable, and durable. A new cross-section for pre-stressed concrete post-tensioned girders (PSC-PT girders) to the highway standard of loading, satisfying all the above requirements, was evolved and discussed in this study. The discussion of the critical literature review, which shows the background of the study, is provided further. Certain prefabricated bridge elements reduce the time spent at the construction site and reduce the effects on road users and the surrounding community. The more the usage of prefabrication, the lower the costs [2]. The modular PSC girders have been conceived principally for bridge construction if adaptable with only slight modification [3]. Adjacent precast multi-beam bridges without diaphragms are prone to longitudinal cracking problems in shear keys. Transverse post-tensioned design of adjacent, precast, multi-beam Bridges was suggested by [4]. It is not feasible in the ROB case over the electrified and busy running track, as in the present study.

A new method of transverse detailing to improve the transverse connectivity has been provided and developed in this project. An experimental investigation conducted by FHWA focused on the structural behaviour of a newly developed bridge girder cross-section, the pi-girder 7.6m long pre-tensioned PSC girders [5], gave much information towards the experimental study conducted presently. A wide range of construction techniques, processes, and technologies, designed to maximize bridge construction or reconstruction operations, minimizing project delays and community disruption, were given in [6]. Prefabrication of the bridge superstructure is the prime aspect of the ABC method. New ideas are required to address the dual needs of faster construction and long service life [6]. The Finite Element 3D static modelling in the

ABAQUS and CDP model employed to model the constitutive behaviours of UHPC, and study of structural behaviour done on 'I'- girder and pi- girder [7] [8], were supporting references for the present study. Even though diaphragms played a significant role in maintaining structural integrity and allowed the cross-section of the pi-girder to carry the applied loads [8], here, the design situation does not allow the usage of in-situ metallic diaphragms. The results of the prototype bridge double-T-unit of 15.24m length tested showed that the 102mm thick cast in place deck integrated the girders. Further, wooden blocks were placed at the bottom of the single common form to reduce the depth to suit smaller spans [9]. The development of a series of optimized sections of pi-girders suitable for span lengths up to 41m and FE model simulation of the structural behaviour of prototype pi-girder with reasonable accuracy [10] supported the present work. Nonlinear behavior has to be considered for concrete structures since they do not behave strictly linear [11]. The addition of a concrete deck can restore or improve load distribution for a deteriorated structure where the shear keys have failed, and the load distribution for the rehabilitated structure corresponds well with current design equations. The use of a concrete deck function as the primary load distribution mechanism of an adjacent box-beam bridge [12]. The shear distributed more broadly to adjacent girders when the ratio of longitudinal to transverse stiffness is low. (Longitudinal stiffness- girder composite longitudinal moment of inertia divided by cube of span length and transverse stiffness- transverse deck strip moment of inertia divided by cube of beam spacing) [13].

In the present study, the girders are found as of this category, and hence the study could be limited to the flexural part. The grillage models were computationally simple compared to the 2D and 3D FEMs, and appeared to be nearly accurate [14]. Although grillage method is the least computationally demanding modelling method of all, it requires experience, judgment, assumptions, and time from the modeller, when descretizing deck into frame elements. Similar methods of grillage and 3D FEM modelling were adopted in the present study also, including the support / boundary conditions.

3 EVOLUTION OF NEW CROSS-SECTION

Bridge superstructure made with multiple precast units of restricted depth and suitable shape will satisfy the design situations like speedy completion without much train traffic disturbances. The application of high strength high-performance concrete to make PSC-PT girders helped to achieve enhanced structural performance. During night hours across the railway track, the girder launching to place accurately on bearings is very difficult. Solid ends for the girders avoid this difficulty. The top of the pier cap can be smooth plastered with CI borings and cement with 1:1 proportion for seating the girders. The seating pressure is very low. A chamfer of 25mmx 25mm providing at pier cap edges will permit the required rotation at supports. The new cross-section allows the usage of a modular shutter, which reduces the cost of construction. This modular shutter with minimum modification is suitable for a family of medium span girders ranging from 15m to 45m. The critical span of 45m, having maximum span to depth ratio, was analyzed with three girder assembly on the conservative side to observe the deflection due to vehicular traffic and within the limits of span/800.

An additional layer of reinforced concrete connects the compression flange of all girders without any formwork. Fixing the crash barrier and the high-rise parapets as protection from the electrified track can be on this layer of concrete. During the rehabilitation of the bridge, due to the increase of span, the demolition of the bridge is possible by cutting the top slab and separating it with screw jacks and jackhammers. Reuse of girder is possible by modifying the same, and hence it is possible to achieve sustainable development in this field.

4 STRUCTURAL REQUIREMENT OF NEW CROSS-SECTION

4.1 Dimensioning and standard of loading

The dimension arrived at the top of the girder is 1.7m as a standardized dimension. This dimension is suitable to make general deck widths of 8.6m, 10.3m, and 12m with a 25mm gap between each girder unit.

The following standards of loading (i) 70 R wheeled loading of single lane and (ii) Two lanes of Class A loading, conforming to IRC:6 2014 [15], were considered for the design of bridge decks. The top width of the girder accommodates nearly 50% of 70R wheeled loading, which is only critical among the two standards of loading.

The dimension of every part of the girder satisfies durability concepts, strength, and serviceability criteria that conform to IRC:112 2011 [16].

4.2 Shape of the girder

The restricted depth girder was developed with two webs to accommodate required tendons and be safe in the ultimate limit state for flexure and shear. Stability also gets ensured by the shape of the girder. The Solid end of the girder helps to accommodate anchorage zones of tendons. The inward pressure from tendons due to the plan profile counteracts the tendency to outward spreading of the webs during loading on the girder. A semicircular arch shape eases out the difficulty in the removal of the internal shutter. Thus, evolves the girder cross-section with flanged inverted U at the middle, similar to the pi-girder, and a flanged solid rectangle at supports with two slow transition zones. Typical cross-section of girder designed for 15m as effective span is shown in Figure 1. (All the dimensions are in millimetres).

This cross-section reduces the depth of girders to 50% than that of regular shaped 'I'-girders and steel composite girders. De-shuttering of the internal shutter before the prestressing helps to increase the efficiency of prestressing. Shear friction reinforcement in the form of diagonal steel maintains the integration between each unit.

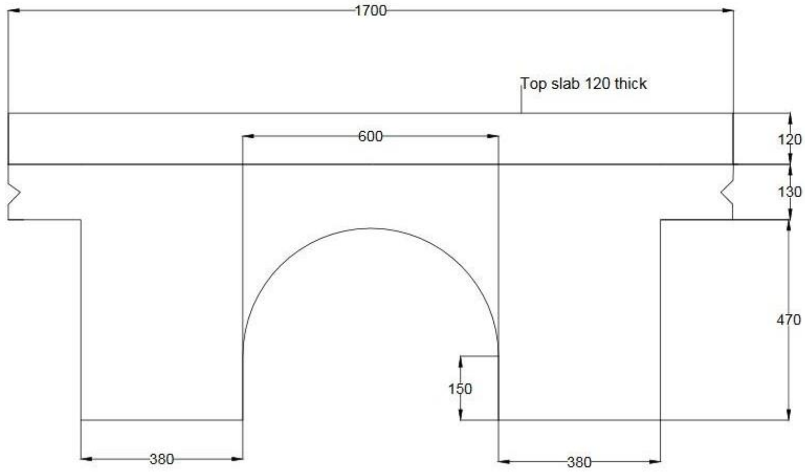


Figure 1. Typical dimensions of girder for 15m effective span cross section

5 EXPERIMENTAL STUDY ON GIRDER SPECIMEN

The dimensional details of the girder specimen cast for the experimental study are depicted below in Figure 2.

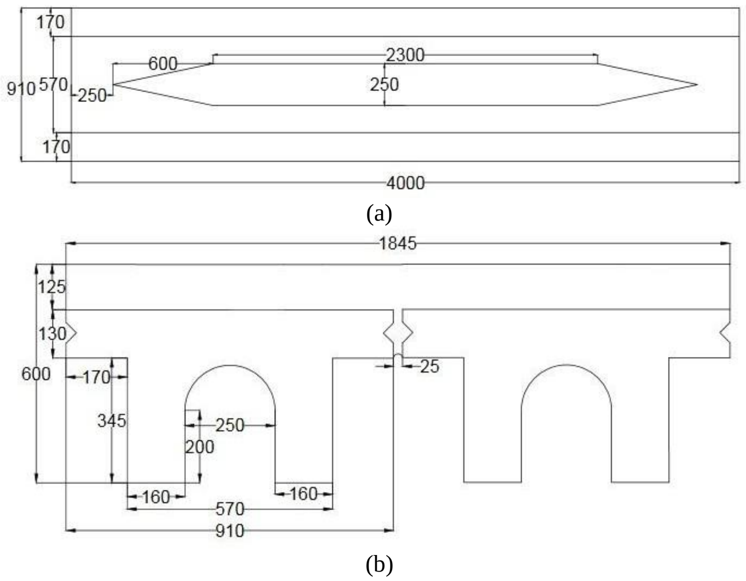
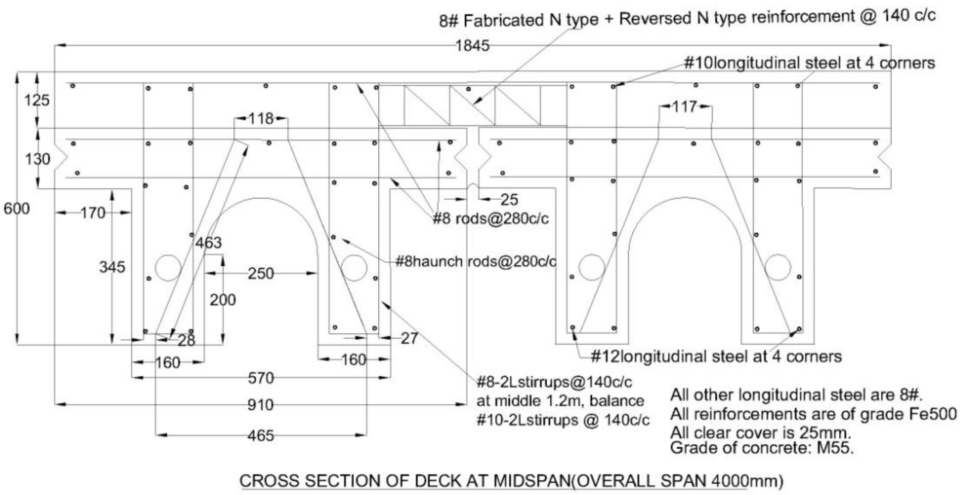


Figure 2. Details of miniature girder and slab (a) Bottom view of single girder and (b) Cross section of deck at mid-span (Overall span 4000mm).

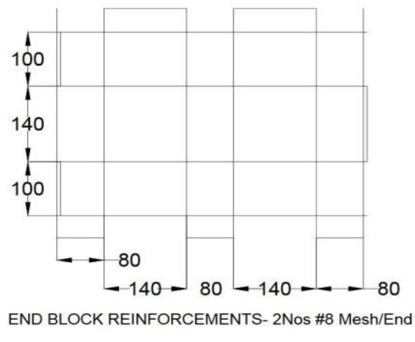
All the above dimensions of the specimen girder were to accommodate the minimum number of prestressing strands and end anchorages, keeping almost the same thickness and cantilever projection of top flange and the integrating slab as of prototype girder. The inner straight vertical dimension was kept as 1.25 times the web thickness, maintaining almost the same maximum ratio as the prototype. The adopted dimensions were suitable to conduct the load test in the laboratory atmosphere. The total load was within the capacity of a 5T crane available in the laboratory.

5.1 The reinforcement details of girder specimens

Minimum steel is not required where the concrete is in compression under the rare combinations of loads and characteristic value of prestress.



(a)



(b)

Figure 3. Reinforcement details of girder specimen (a) at midspan and (b) at end block

However, minimum reinforcement for other considera-tions such as early thermal and shrinkage cracking, before prestressing, was provided as per IRC:112 2011. Figures 3(a) and 3(b) show the reinforcement details of the specimen girder at the midspan and end block. The potential issue of the longitudinal crack, in the case of a multi- girder deck, could be solved by designing and detailing the monolithic deck slab of 120mm (125mm with construction tolerance in specimen) thick for the shear friction effect generated during undefined vehicle movement. The deck above the joint was provided with N-type and reversed N-type fabricated steel of 8mm in diameter, as depicted in figures 3(a).
Photos 1(a), and 1(b) show the arrangement of reinforcements and sheathing.

(a)

(b)

Photo 1. Arrangement of reinforcements and sheathing (a)Top view and (b)side view

5.2 The mix design

The mean compressive strength of the mix adopted was 65MPa. The corresponding characteristic strength was 55MPa, as given in table 1. This mix was adopted due to the less availability of materials.

Table 1. Mix design

Cement (kg/m^3)	Crush sand (kg/m^3)	Silica fume (kg/m^3)	Coarse aggregate (kg/m^3) 20mm	Coarse aggregate (kg/m^3) 12.5mm	Plasticizer (Auromix 500)	W/C ratio	Compressive strength (Mpa)
440	657	40	671	445	2.26	0.31	67

The ready-mix concrete (RMC) with this proportion was prepared and supplied to the structural lab by a reputed agency to cast the girder. The RMC was adopted to simulate the general condition of Bridge Construction. The authors cast two such girders on the lab floor itself. Photo 2 shows the stages of casting.

Photo 2. Stages of casting, a) Concreting using ready mix, b) needle vibration, c) Concreting completed, d) Wet sack curing, e) & f) sampling

5.3 Prestressing of girders and casting of deck slab

After 14 days of casting, one-end stressing was done for the girders with a single pull jack and grouted on the same day using a grouting pump and agitator. The removal of inner and bottom shutters was after stressing one strand from each cable by keeping the girder in an elevated position, using a crane. The jacking force was 0.7 UTS (Ultimate Tensile Strength). The precast-prestressed girders were placed on the support of 200 mm width, keeping a 25mm gap in between the girders. Slab reinforcements got tied as per the detailed drawing. These reinforcements include the N-type and Reverse N-type welded steel to cater to the shear friction effect. The 25mm gap and the shear key were concreted first with the same mix after closing the joint bottom using a poly-foam of 5mm in 5 layers. The mix design adopted for concreting the shear key was with small size aggregate. Photo 3 shows the stages of pre-stressing and casting of the integrating slab.

(a) (b) (c)

(d) (e) (f)

Photo 3. Stages of pre-stressing and casting of integrating slab, a) Arrangement of strands including one dummy strand, b) Prestressing, c) Removal of interior shutter after stressing one strand from each cable, d) Grouting, e) Launching of girders at 25mm gap, f) Deck slab reinforcement including for shear friction.

(g) (h)

Photo 3. Stages of pre-stressing and casting of integrating slab, g) Concreting of deck slab and h) Curing of deck slab.

6 DISCUSSION OF LOAD TESTING AND RESULTS

The deck made with two specimen girders named PTGR1 and PTGR2, was load tested against two-point loading. The application of two-point loading to the bridge deck was through the column type jack having a load capacity of 75 t (1t= 1000kg) attached with a load cell capacity of 50 t. The strain gauges were fixed to the bottom and top of each web of two girders at midspan to measure the tensile and compressive strains. Four numbers of linear variable differential transformers (LVDTs) of travel length 0-200mm were fixed at the bottom of each web to measure the deflections. One LVDT of travel range 0-5mm arranged at the midsection was used to assess the spread of the same. The loading frame uplift and support settlement during the loading of the deck were measured using another two LVDTs of the range 0-5mm.

6.1 Order of load testing

The first and second test loadings were applied concentrically and eccentrically on the deck above PTGR1 on the two-girder assembly of the deck. Photo 4 shows the arrangements in the order of load testing. The concentric load testing was conducted only up to 25 t to stay within the elastic behaviour of deck assembly and further tested for eccentric loading on the two-girder assembly of the deck. Two individual girders and slab assembly, on PTGR1 and PTGR2, were tested finally for two-point loading. The load placement was eccentric on the web to reach the peak load at the earliest (this condition does not exist in actual girder-deck assembly). This testing was conducted with two jack assembly, as seen in Photo 4(g) and 4(h). The first crack was at a total load of 50 t. The peak load tested on PTGR1 assembly was 66 t, and that of PTGR2 was 77.35 t.

Photo 4. Arrangements in the order of load testing, a) Two point load testing arrangement, b) Data logger connected, c) Arrangement of LVDTs and Strain gauges at mid span, d) Close view of centralised load testing arrangement, e) Strain gauge fitted to compression, f) View of eccentric load testing arrangement, g) Enlarged view of load testing on PTGR1, and h) Load testing on PTGR2

6.2 Results and discussion

a) Test 1

The concentric load testing on double girder deck assembly (PTGR111) showed the following behaviour;

- The deflection of each web under different load increments was plotted against the web's cumulative distance from one end web. All the graphs corresponding to each load, are showing a linear pattern, as in figure 4. It reflects the excellent integration between girders achieved mainly due to the top deck slab, the shear friction reinforcement embedded inside the deck slab, and the diamond-shaped shear key.
- The deflection of each web for this concentric load testing was observed, and found that the load sharing between two girders is 85% to the loaded girder and 15% to the offloaded one.

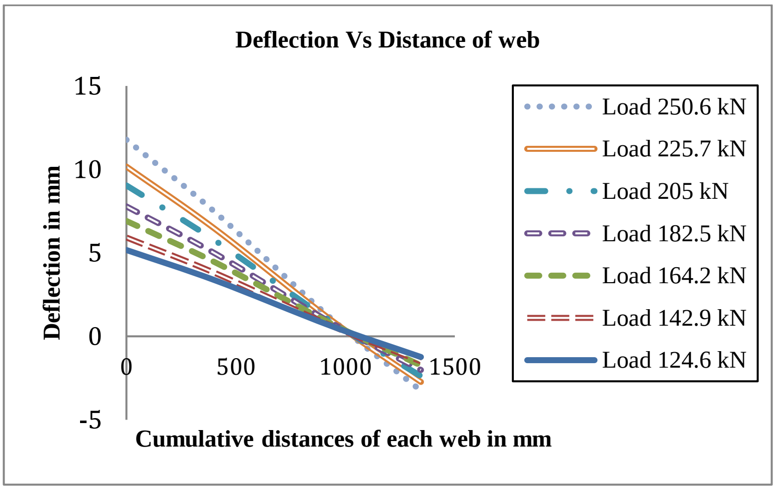


Figure 4. Deflection Vs cumulative distance of webs from one end for load ranging from 124.6 kN to 250.6 kN (PTGR111- concentric load testing)

b) Test 2

The eccentric load testing on double girder deck assembly (PTGR112) showed the following behaviour;

- The deflection of each web under different load increments was plotted against the web's cumulative distance from one end web. All the graphs corresponding to each load, are showing a linear pattern, as in figure 5. It reflects the excellent integration between girders achieved mainly due to the top deck slab, the shear friction reinforcement embedded inside the deck slab and the diamond-shaped shear key.
- The deflection of each web for this eccentric load testing was observed, and found that the load sharing between two girders is 77% to the loaded girder and 23% to the offloaded one.

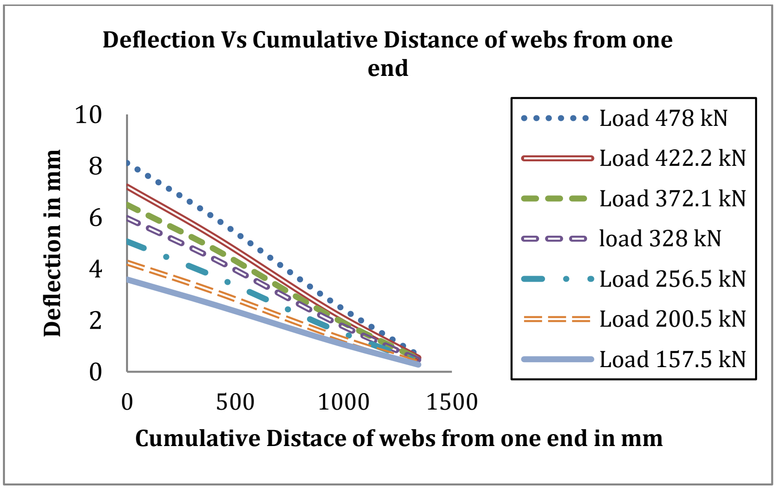


Figure 5. Deflection Vs cumulative distance of webs from one end for load ranging from 157.7 kN to 478 kN (PTGR112- Eccentric load testing))

Among the above two tests, eccentric load testing is critical to decide the load sharing between girders practically.

Further, the two-girder assembly got separated and conducted the two-point testing on individual girder-deck assemblies. The constitutive material properties to adopt in Concrete Damaged Plasticity (CDP) modelling could be arrived at through the modelling section discussed below.

7 MODELING OF STRUCTURAL PERFORMANCE

The CDP model of ABAQUS software was primarily employed to model the constitutive behaviours of the high strength high-performance concrete post-tensioned twin-T girders (Specimens) through first-order non-linear analysis. The density of concrete taken from the cube test was 25350N/m^3, and the Poisson's ratio applied was 0.19. The Young's modulus was assumed to be 32GPa, and the maximum tensile stress and the ultimate tensile strain in the concrete were taken as 3.0 MPa and 0.0003, respectively. These two values were obtained by calibrating the finite element models to the experimental results of two twin-T girders. The applied values of the elastic compressive limit, the ultimate compressive strength and the corresponding compressive plastic strains were; 35MPa, 65MPa, and 0.002, respectively. The Young's modulus (E), obtained from the cylinder test, was applied in the software. The authors developed three-dimensional twin-T girder models to calibrate HS-HPC properties and simulate both linear and non-linear behaviour of the twin-T girder under various tests, as shown in figures 6, 7, and 8. The figure covers the whole model, including the reinforcing bars and strands embedded in the HS-HPC. The partitioning done on the girders facilitated the definitions of the loading surface and for easy and correct meshing. For strands and concrete, a continuous-solid element with reduced integration, C3D8R, was used. The prestressing force was calculated manually and applied as predefined stress. The girders, meshed with 65mm global seeds, were studied again with 45mm meshes for mesh consistency. Since the results were converging by 95% and fine mesh produces more accurate results, the results adopted correspond to the 45mm mesh for the study.

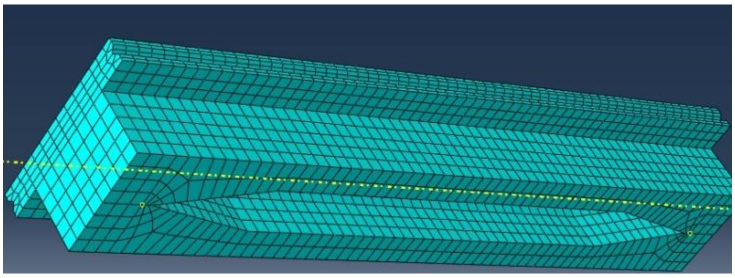


Figure 6. View of meshing

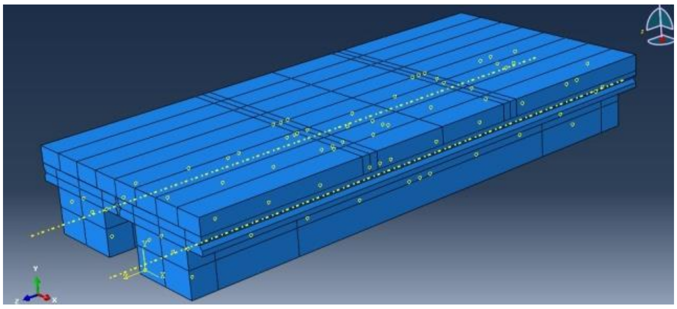


Figure 7. Assembly of deck

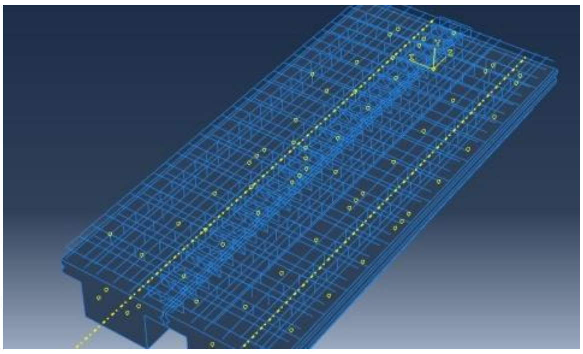
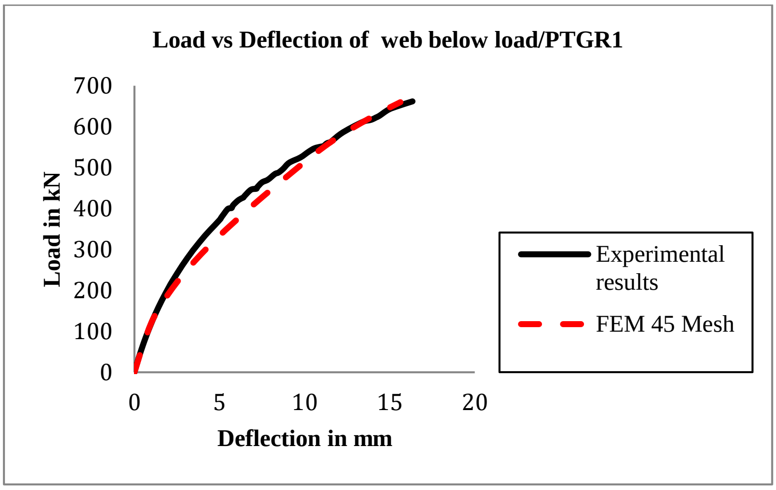


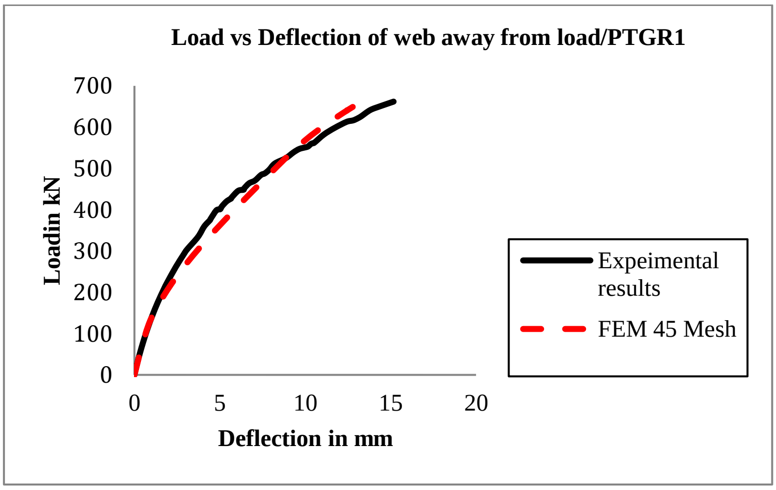
Figure 8. Arrangement of N-type & reversed N-type steel

7.1 Calibration and validation of results

The test results on individual girder and deck slab assembly, on PTGR1 and PTGR2, were compared with the FEM study through the load-deflection curves in Figures 9 and 10. There was excellent agreement between the FEM and experimental results.

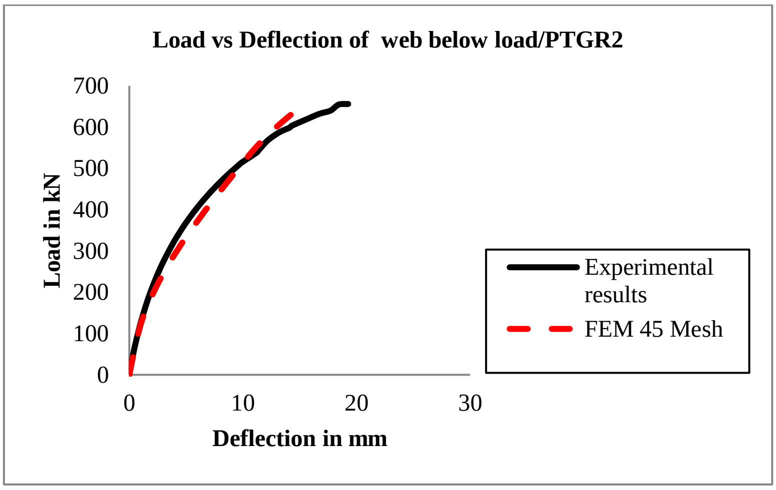


(a)

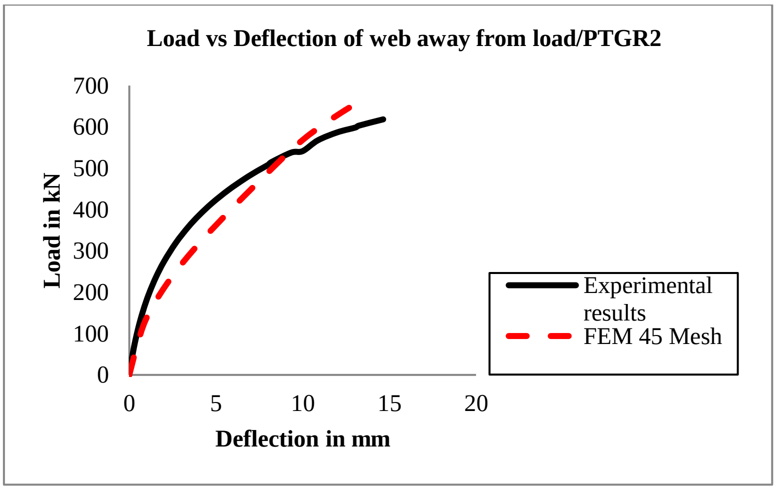


(b)

Figure 9. Load-deflection curve for PTGR1, a) of web below load, b) of web away from load



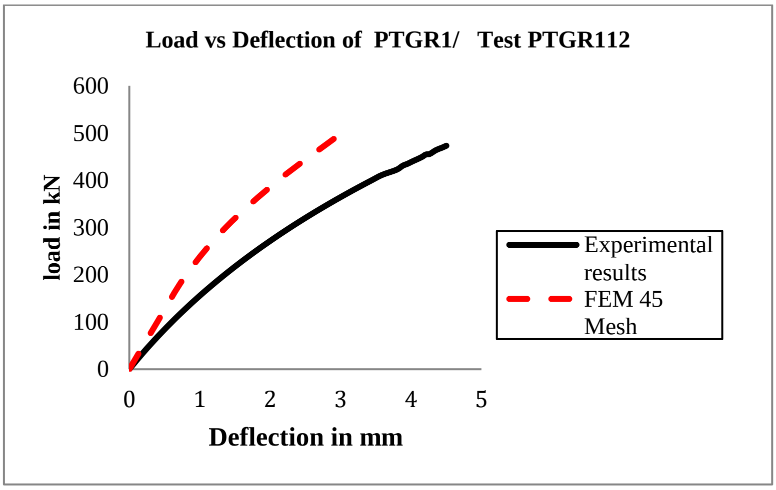
(a)



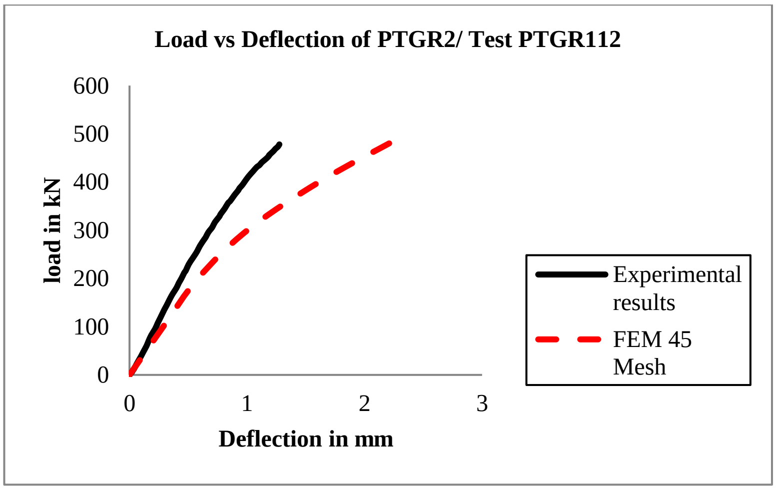
(b)

Figure 10. Load-deflection curve for PTGR2, a) of web below load, b) of web away from load

Further to the above comparison on single girder tests, the behaviour of Double girder assembly with a diamond-shaped shear key joint, and the integrating deck slab over two girders with designed shear friction reinforcement, was also compared for Load Vs Deflection in figure 11.



(a)



(b)

Figure 11. Load-deflection curve for double girder assembly (PTGR112), a) of first girder, b) of second girder

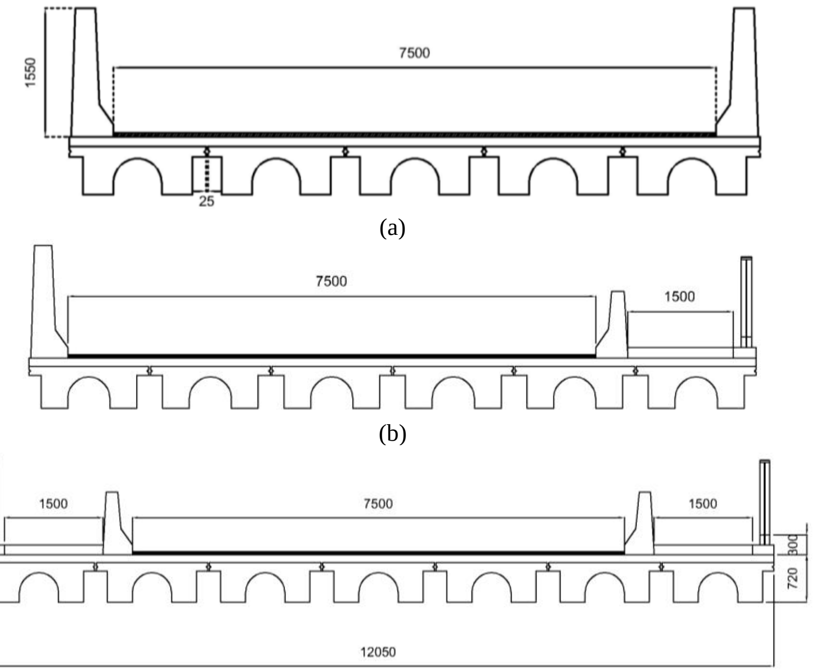
The authors adopted a customized coefficient of friction 0.1 in the analysis between girder and shear key. The load application was on the second web of the first girder. The above graph shows more load sharing to the second girder in the FEM analysis than that of the test results, which reduces the maximum deflection. Hence, an enhancing factor was arrived to decide the depth of girder of each span to keep the structure within the vehicular deflection limit of span/800. The FEM graphs agree with the experimental results in general.

7.2 Salient features of modelling

- E = 32 GPa.
- The maximum tensile stress and the ultimate tensile strain in the concrete were taken as 3.0 MPa and 0.0003, respectively.
- Friction coefficient is 0.3 for single girder assembly and 0.1 for the contact of the shear key.
- Load applied was 650kN on a single girder and 1000kN on the double girder.
- The Prestressing force was applied as predefined stress calculated after all the losses.
- Boundary condition- maintained the displacements at ends.
- Default values of plastic parameters were applied.

8 GENERAL ARRANGEMENT OF HIGHWAY-DECK WITH NEW TWIN-T CROSS-SECTION

Figure 12 and 13 show deck arrangement for various width of road and the cross-section and bottom view of Twin-T-girders of span varying from 15m to 45m. The preliminary design for various spans were done and the 45m span (of maximum span to depth ratio) deck with three girders was analyzed using the developed model.



(c)

Figure 12. Typical arrangement of (a) five girder assembly (b) six girder assembly with one side footpath (c) seven girder assembly with footpaths on both sides.

The figures 14 and 15 show the FEM results of vertical deflection and the horizontal deflection. The vertical deflection is 9.7mm which is within the limits of span/800 (56mm) and the horizontal deflection is zero indicating no spread.

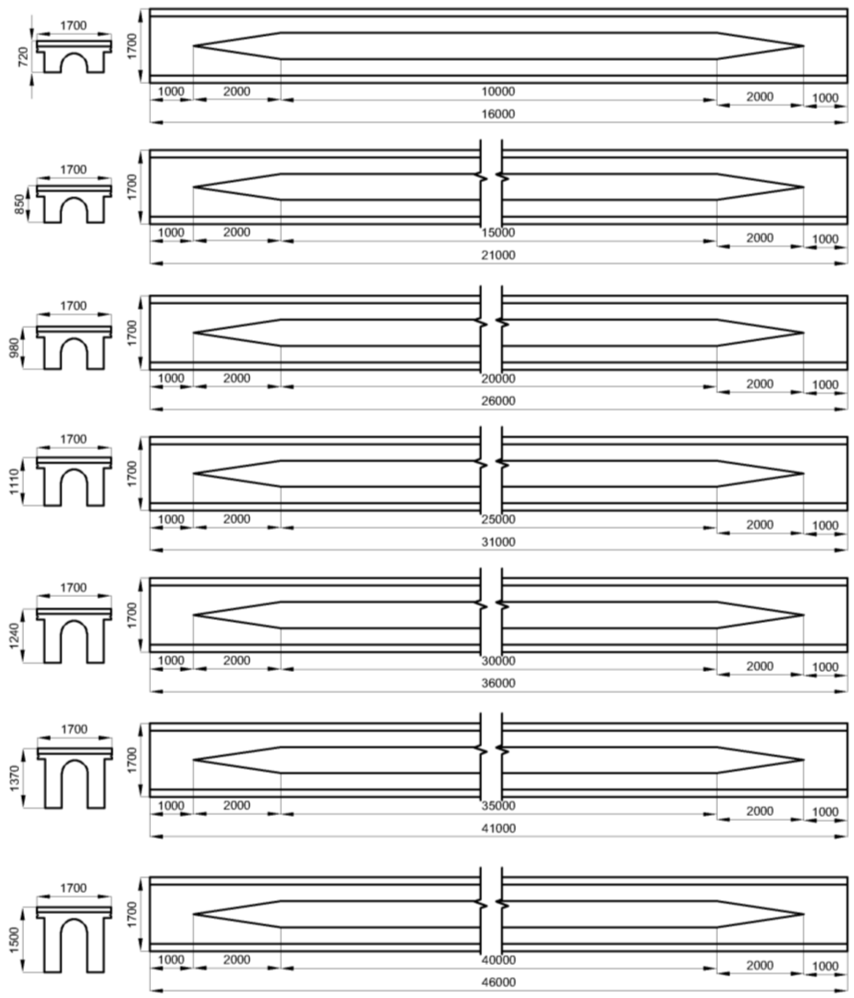


Figure 13. Cross-section and bottom view of Twin-T-girders of span varying from 15m to 45m.

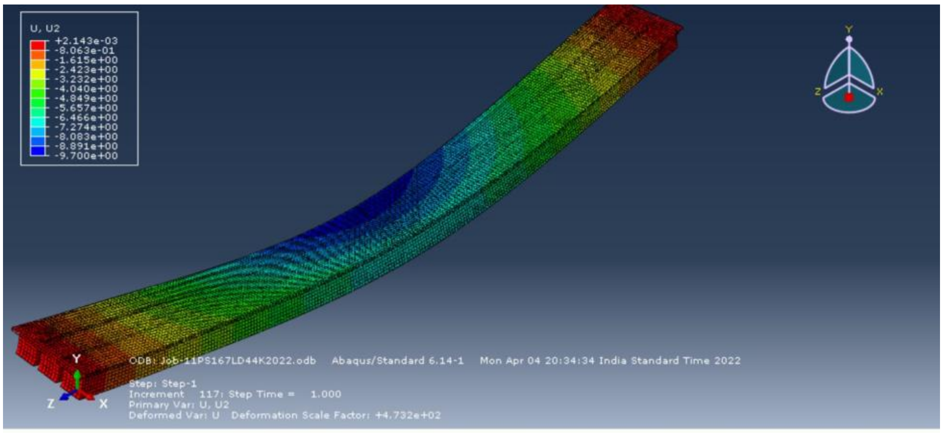


Figure 14. The displacement U2 at midspan of 45m girder

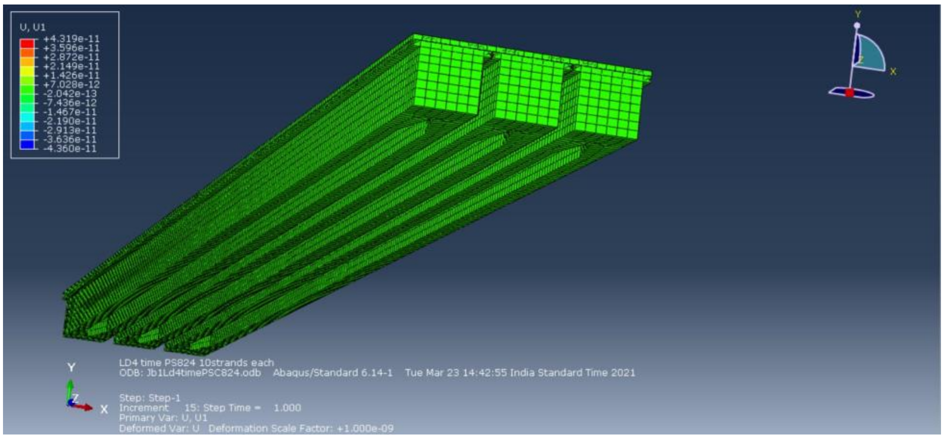


Figure 15. Values in legend shows lateral deflection is nearly zero

9 CONCLUSIONS AND FUTURE WORK

The authors illustrated that the typical cross-section of PSC-PT girder, in multiple units and deck-assembly, adopted in this study, is effectively transferring the highway standard of loading. Hence, the main conclusions of this study and future works are listed here;

- Developed a new Twin-T cross-section as suitable for standardization of span decks ranging from 15m to 45m.
- There is proper integration between girders and deck slab due to special shear friction reinforcements and shear keys provided.
- The minimized depth of construction was due to the evolved shape of cross-section and the HS-HPC PSC-PT girders, which reduces the land requirements and any modifications of existing junction/bridges, if any, in

the approaches.

- Due to the shape of the cross-section, the casting of the integrating deck slab above the precast girders required no formwork, and hence no train traffic block is needed except for the launching of girders.
- Achievement of accelerated bridge construction becomes possible through standardization and modularization of the bridge superstructure.
- The FEM analysis is helpful for the study of the behaviour of multiple girder assembly of various spans ranging from 15m to 45m.
- In future, it is suggested to conduct experimental study on prototype girders or performance study on actual bridge deck made of Twin-T- girders. It will help to reveal more about the structural performance of these standardized and modularized restricted depth highway girder assemblies

ACKNOWLEDGEMENT

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